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ORIGINAL PAPER

Biomass production of hybrid aspen growing on former farm land in Sweden

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Abstract: We construct dry weight equations for hybrid aspen growing on former farmland in Sweden. Dry weight equations for fractions of hybrid aspen trees were also made. We estimated biomass production in 24 stands. The stands were located in Sweden at latitudes ranging from 55 to 60º N. The mean age was 18 years (range 15-23), the mean stand density 1090 stems·ha^{-1} (range 378–2374), and the mean diameter at breast height (over bark) 178 mm (range 85–244 mm). Soil types in the hybrid aspen stands were mainly clay (21 stands), tills (2 stands) and other (1 stand). The mean total standing dry weight above stump level (≈ 200 mm) for the hybrid aspen stands was 135±53 t·ha^{-1} with a range of 42–219 t·ha^{-1}. In addition to estimating conventional dry weights of trees and tree components, basic density, specific leaf area (SLA), projected leaf area (PLA) and leaf area index (LAI) were estimated and were in agreement with published figures.

Keywords: basic density; biomass production; farmland; hybrid aspen; MAI; plantation forestry

Introduction

Hybrid aspen has been planted on forest and farm land and studied in Sweden, Finland, Norway, Denmark, Baltic States and in the Great Lake Region in US (Benson and Einspahr 1967; Li and Wu 1998; Dickman 2001; Yu et al. 2001; Rytter and Stener 2003; Karačić et al. 2003; Tullus et al. 2012). Hybridization between the European aspen (*Populus tremula* L.) and the American aspen (*Populus tremuloides* Michx.) was first described at the beginning of the 1920s in Germany (Wettstein 1933). In Sweden the first crossings between *Populus tremula* L. and *Populus tremuloides* Michx. were made in 1939 (Rytter and Stener 2005). Plantations of hybrid aspen even on farmland must be fenced against wild habitat (moose (*Alces alces* L.), deer (*Cervus elaphus* L.), roedeer (*Capreolus capreolus capreolus* L.), hare (*Lepus capensis* L., *Lepus timidus* L.), rabbit (*Oryctolagus cuniculus* Pallas) and vole (*Microtus agrestis* L., *Arvicola amphibious* L.)). Plantations on forest land in Sweden are sparse and not recommended depending on the high wild habitat population. There are some Nordic results from hybrid aspen trials established in the period 1940 to 1960 (Johnsson 1953, 1976; Langhammer 1973; Jacobsen 1976; Eriksson 1984). Mean annual increment (MAI) for the measured trials varied between 12 and 17 m^3·ha^{-1}a^{-1} (≈4.2–6.0 t·ha^{-1}a^{-1}). An advantage with hybrid aspen as well as the parent species is the rapid establishment and fast growth of the second generation. Hybrid aspen produces 50,000 to 100,000 suckers after cutting (Rytter 2006). In a German study the number of suckers per hectare established after harvesting the first plantation (10 years) was 165,000 and after the second rotation (10 years) the number was 215,000 (Liesebach et al. 1999).

During the last 20 years, there has been a general increase in interest in the management of broadleaved trees in the Nordic countries (and elsewhere), despite the lack of suitable climate-adapted clones and uncertainties regarding appropriate management, pest control, economic factors, markets and future land-use policy at both EU and national levels etc. The earliest cultivation of hybrid aspen in Sweden started in the end of the 1930s (Johnsson 1953, 1976; Langhammer 1973). In the late 1940s the Swedish Match Company showed strong interest in hybrid aspen as a fast growing and high yielding species. A breeding program was started mainly focused on fast growing individuals with a high yield (Rytter and Stener 2005). Later on in the 1980 the objective for hybrid aspen cultivation changed to focusing on the specie as a crop on former farm land. Today there is an increasing interest in biofuel as an energy supply. In Sweden the main biofuel sources are tops and twigs collected after clear cuttings. Among other crops useable as biofuel hybrid aspen is important specie to test (Karlsson 1991; Christersson 1996; Ilstedt and Gullberg 1993). In Sweden hybrid aspen is

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mainly used as pulpwood, wood for matches and in a small scale as plywood. These scenarios might be an interesting alternative both on farmland and on fertile forest land. Then with the use of hybrid aspen wood for different purposes in Norway and Finland there are existing markets for hybrid aspen pulpwood, saw logs and biofuels. Few studies dealing with biomass yield from hybrid aspen stands growing on farmland are published.

The present study is a part of a series on the biomass of broadleaf species, either planted or self-generated, and growing on forest or farm land (Johansson 1996, 1999a, 1999b, 1999c, 1999d, 2000, 2002, 2006, 2008; 2011; Johansson and Karačić 2011). Since reports on leaf characteristics for hybrid aspen, such as projected leaf area (PLA), leaf area index (LAI) and specific leaf area (SLA), are sparse but important structural parameters of forest ecosystems, leaf and canopy measurements were made. Leaf characteristics, mainly LAI, have an important influence on the exchange of energy, gas and water in trees. LAI is a key component of biochemical cycles in ecosystems (Bréda 2003).

The aim of the present study was to construct dry weight equations for hybrid aspens and their above-ground components. Constructed biomass estimation functions were used for calculating biomass production for plantations on former farmland. The effect of age and density on biomass production was analyzed by the constructed biomass function. Characteristics such as LAI, SLA and PLA were estimated and calculated for both individual trees and entire stands.

Material and methods

Study site

In this study, we evaluated 24 stands of hybrid aspen growing on former farmland. The study area is located between latitudes 56º and 60º N in Sweden (Fig. 1 and Table 1). No information about clones was available but the material was a hybrid between European aspen origin lat. 56−57° N. and American aspen origin lat. 43−54° N. However later on in 2000 it has been introduced improved clones c.f. Stener and Karlsson (2004). The age of the stands ranged from 15 to 23 years and the stem number ranged from 378 to 2374 (Table 1). Initially 1100−2500 stems per hectare was planted. Thinning operations have been made only in stands no. 3, 13 and 23. The thinning removals were 50% of initial stem number (1500, 2500 and 1100 respectively). The low stem numbers in some of the studied stands indicate loss of stems caused by among others wild habitat. As the stands were established on farmland no other tree species than hybrid aspen were growing on the site. Early growth and damage to the plantation were assessed on the basis of information provided by the forest owner.

Sampling and measurements

The mean number of stems per hectare was calculated based on the number of stems counted in either whole stands or plots, as follows. The area of the studied plantations varied between 0.09 and 2.40 ha. In stands > 1 ha stands, a 0.5 ha plot in the central part of each stand was chosen: The outer row in the stand was not included avoiding edge effects caused by factors such as wind, open areas, ditches and shading by adjacent stands). The diameter at breast height (DBH) of each counted tree was measured by cross callipering (Table 1), and the arithmetic mean diameter was calculated for each stand.

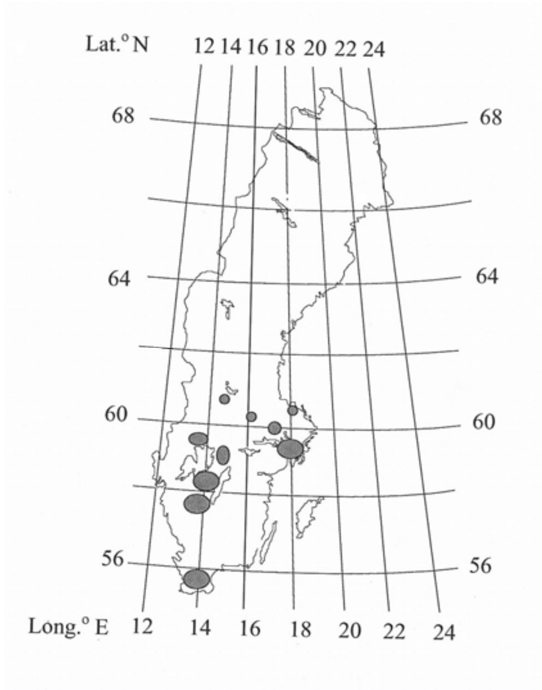

Fig. 1 Localities of sample trees of hybrid aspen growing on abandoned farmland in Sweden.

For calculation of mean height in the hybrid aspen stands a statistical regression model for each stand was made. The height and diameter for 9 trees in two subsample plots each was measured. The two subsample plots (3 trees by 3 rows close to each other) were systematically located e.g. the first measured tree was the fifth tree in the third row. The other subsample plots started in the opposite part of the stand area diagonal to the first plot. Then a regression model for each stand describing the relation of height to diameter was made. Tree mean height on the plots was calculated by the regression models.

In each stand, one hybrid aspen with a diameter close to the estimated arithmetic mean diameter was selected. This tree was then assessed in terms of damage, stem straightness, and leader type (single vs. double or broken). The tree also had to be free from root rot. If any tree was damaged or rotten, it was not used, and another from the stand was selected instead. The trees were felled and cut as near to the ground as possible and their height (cm) were measured (Table 2) and DBH (mm) was recorded. The age of these trees was determined in the laboratory by counting annual rings in discs taken from the base of the stem (total age) and breast height (breast height age). The stem was weighed fresh in the field. All twigs on the tree were then cut and weighed with leaves. Since the sampling procedure to quantify the leaf mass is very laborious, a "mean leaf technique" method was used

for dry mass estimation. All leaves from three hybrid aspens from each of three localities, totally 9 trees, were sampled and weighed fresh. The samples were taken from trees with stem diameters of 100, 200 and 300 mm DBH. Then a simple allometric equation was derived, relating DBH to percentage fresh leaf weight by fresh weight of twigs + leaves, and used for estimating the leaf weight of all sampled trees.

Table 1. Main characteristics of sampled hybrid aspen stands growing at 24 locations in Sweden

Plot No	Age, years	Height, m mean±SD	DBH, mm mean±SD	No. of stems ha^{-1}	Basal area $m^2 \cdot ha^{-1}$	Soil type	Stand/plot size, ha
1	19	11.8±2.9	126±62	850	10,6	Sandy silty till	0.09/0.08
2	18	22.5±2.1	191±39	1467	42,0	Light clay	0.11/0.09
3	19	25.8±2.0	224±32	710	28,0	Light clay	0.42/0.40
4	19	20.8±1.5	237±42	432	19,0	Light clay	0.08/0.07
5	19	18.3±3.5	167±40	814	17,8	Light clay	0.08/0.07
6	19	14.9±3.7	140±44	650	10,0	Fine sand	0.09/0.08
7	17	19.7±2.8	158±44	1540	30,2	Medium clay	0.09/0.07
8	17	17.1±2.5	125±26	2232	27,4	Light clay	0.19/0.18
9	17	16.5±1.6	157±34	844	16,3	Medium clay	0.10/0.09
10	23	20.2±1.8	197±23	1050	32,0	Light clay	0.10/0.08
11	19	17.5±3.4	173±44	1370	32,2	Light clay	0.11/0.10
12	19	15.5±3.3	147±40	1760	29,9	Light clay	0.13/0.10
13	17	16.9±2.1	161±41	1150	23,4	Light clay	2.40/0.50
14	17	19.4±1.8	235±33	486	21,1	Light clay	0.26/0.24
15	20	20.6±1.7	162±31	567	11,7	Medium clay	0.11/0.10
16	18	25.0±2.3	237±59	779	34,3	Light clay	0.12/0.10
17	16	10.4±1.4	85±26	1259	7,1	Light clay	0.09/0.08
18	16	14.6±2.0	150±46	2000	35,3	Light clay	0.09/0.08
19	15	16.0±1.8	142±25	2374	37,6	Medium clay	0.13/0.12
20	18	20.8±1.5	179±38	1600	40,2	Light clay	0.13/0.11
21	19	22.6±1.7	225±39	378	15,0	Sandy silty till	0.31/0.30
22	19	24.1±2.1	239±63	468	21,0	Medium clay	0.36/0.35
23	20	22.2±1.0	244±32	593	27,7	Medium clay	0.20/0.18
24	20	20.8±2.0	181±44	785	20,2	Light clay	0.22/0.21
Mean±SD	18±2	18.9 ±3.9	178±43	1090±585	24.6±10.0		
Range	15-23	13.5-25.8	85-244	378-2374	7.1-42.0		

Samples of stem and twigs were taken for estimating basic wood density. A disc at 4 m height was taken. Four samples of twigs (10 cm long) were taken close to the stem base, two in the upper and two in the lower part of the crown. The basic density of stems and twigs was estimated according to the water-immersion method described by Andersson and Tuimala (1980). Samples of stems and twigs were saturated in water for 24 h and then weighed and their volume (cm^3) was determined. The dry matter content of the wood proportion (g) of the samples was determined after drying at 105°C in an air-ventilated oven for 3−5 days, depending on their dimensions. Dry weight to fresh volume ratios of the debarked disk and twigs were then calculated as basic density ($g \cdot cm^{-3}$) (Table 2).

A sample of 200 leaves from sample trees in all hybrid aspen stands was taken from the top, middle and lower parts of the crowns then frozen for analyses in the laboratory. The 200 sampled leaves were weighed fresh, and the estimation of PLA (projected leaf area), mm^2, of the sample was determined with a leaf-area meter (LI-3000, LI-COR, Inc. Lincoln. Neb.). Each of the samples was then dried at 105°C in an oven for 48 h and weighed. The dry mass of the leaves was then calculated. The specific leaf area, SLA ($cm^2\ g^{-1}$) was calculated as the total leaf area (cm^2) of a tree divided by the dry weight (kg) of the leaf mass.

Within each sample hybrid aspen stand, leaf area index (LAI) was estimated using a LAI-2000 plant canopy analyzer (LI-COR Inc., Lincoln, Neb.). An initial measurement was taken outside the stand then another five readings were taken along each of five transects inside the stand, giving in total 25 estimations from various points within the stand. Measurement locations were both under hybrid aspen trees and in small stand openings. A final measurement was taken outside the stand to calibrate LAI.

Soil samples, down to a depth of 30 cm, were taken from two points in each stand, and the mean texture of the sampled layer was determined. Soils were classified as tills and sediments (Johansson, 1999) in the field, following guidelines provided by Ekström (1926) and then according to particle size in the laboratory. The particle size distribution was determined using a mechanical sieving method (English and German standard), and soil types were classified as follows: sediments as gravel (20-2 mm), coarse sand (2−0.2 mm), fine sand (0.2−0.02 mm), silt (0.02−0.002 mm) or clay (<0.002 mm); tills as gravel, sandy, fine sandy or silty tills; and organogenic soils as moorland peat or moss peat. Although the soil samples contained particles of different size, their type designation was based on the most frequent size, together with one or two prefixes associated with

other less frequent soil types. Clay soils were then classified based on their percentage clay as follows: light clay (13%–29%), medium clay (30%–40 %), heavy clay (41%–60%), and till clay (13%–60%) The water table was estimated to be between 30 cm and 60 cm deep at all sites. Most of the hybrid aspen stands were growing on sediments: 6 on medium clay, 15 on light clay and 3 on tills.

Table 2. Characteristics of sampled trees of hybrid aspen stands.

Locality No	Age, yrs	Height, m	Diameter, DBH, ob	MAI kg yr^{-1}	Basic density, g cm^{-3}	
					Stems	Twigs
1	19	16.7	236	13.0	0.320	0.430
2	18	20.5	223	9.4	0.305	0.293
3	19	23.0	255	13.8	0.295	0.298
4	19	21.1	260	10.4	0.371	0.412
5	19	15.1	221	11.0	0.401	0.328
6	19	17.3	242	7.6	0.345	0.312
7	17	20.0	189	7.2	0.343	0.326
8	17	20.3	145	4.0	0.346	0.533
9	17	17.1	177	5.6	0.290	0.309
10	23	21.2	191	6.4	0.314	0.300
11	19	21.4	206	10.8	0.494	0.432
12	19	17.5	219	9.6	0.459	0.361
13	17	19.6	227	10.8	0.338	0.300
14	17	18.1	270	19.4	0.411	0.489
15	20	18.0	292	16.9	0.343	0.290
16	18	24.3	338	18.1	0.361	0.340
17	15	14.0	149	5.1	0.378	0.333
18	15	17.0	211	9.3	0.371	0.319
19	16	16.5	182	8.6	0.343	0.320
20	18	21.1	242	13.4	0.344	0.316
21	19	21.9	263	13.7	0.313	0.333
22	19	25.4	388	32.9	0.356	0.373
23	20	23.2	310	18.6	0.306	0.341
24	20	22.0	195	8.1	0.400	0.610
Mean±SD	18±2	19.7±2.9	235±57	11.9±6.0	0.356±0.050	0.362±0.083
Range	15-23	14.0-25.4	145-388	5.1-32.9	0.290-0.494	0.290-0.610

Data analyses

The dry mass production per tree was calculated on the basis of an equation describing the correlation between DBH and dry mass production (kg/tree), derived from data collected from all of the measured trees.

The power function was tested:

$$M = \beta_0 \times D^{B_1} \tag{1}$$

where, M is the dry mass, kg tree^{-1}, D is the diameter at breast height, over bark (ob), mm, β_0 and β_1 are parameters.

The power model is frequently used to describe such relationships (Kittredge 1944; Payandeh 1981; Satoo and Madgewick 1985; Bolstad and Gower1990; Johansson 1999). Based on the mean diameter, the actual dry mass production of each of the hybrid aspen stands included in the study was estimated.

Data were analyzed by nonlinear regression using the SAS/STAT system for personal computers (SAS 2006). A measure of the fit of the nonlinear regressions was based on the coefficient of determination (Zar 1999):

$$R^2 = 1 - (SSE/SST\ (corrected)) \tag{2}$$

where SSE is the sum of squares of the error terms and SST is the total sum of squares.

The regression was also tested by root mean squared error (RMSE).

$$RMSE = 1 - \sum (Y_i - \hat{Y})^2 / (Y - \overline{Y})^2 \tag{3}$$

Throughout the report, means are presented together with standard deviation (SD).

Results

Allometric relationships

The tested function (1) fitted the data relating dry mass to DBH for both small and large hybrid aspens and the curves described by the function are statistically acceptable. The value of the determination coefficient (R^2) and RMSE indicate good correlation between the fitted curves and the estimated values. Further information about parameter estimates is given in Table 3.

Table 3. Estimated parameters of Equation (1) for dry weight estimations of hybrid aspen growing on former farmland

Components	Parameter	Parameter estimates	Standard errors of parameters	R^2	RMSE
Total	B_0	0.00666	0.00598	0.97	46.35
	B_1	1.90220	0.15920		
Stem	B_0	0.00273	0.00230	0.97	31.40
	B_1	2.00430	0.14880		
Twigs	B_0	0.00881	0.00002	0.81	28.48
	B_1	1.59260	0.41510		
Leaves	B_0	0.00227	0.00022	0.96	1.94
	B_1	1.92670	0.13530		

Biomass structure for sample trees

The mean total dry tree weight (range within parenthesis) was 218±120 (68–625) kg (Table 4) and MAI was 11.9±6.0 (5.1–32.9) kg year^{-1} (Table 2). Curves relating the dry masses of the various fractions per tree (total dry mass above stump level, stem, twigs and leaves) to diameter are presented in Fig. 2. The mean percentage ± SD of the total dry weight accounted for by the dry weight of stem, twigs and leaves was 72±10 % (51–85), 24±10 % (11–46) and 4±1 (3–7), respectively (Fig. 3 and Table 4). The mean percentage dry matter of fresh weight for stem, twigs and leaves was 54±5 (47–65), 53±5 (46–69) and 37±4 (27–47). Basic density for the 25 sampled hybrid aspen stems varied between 0.295 and 0.494 g·cm^{-3} with a mean of

0.356±0.050 g·cm^{-3} and for twigs 0.362±0.083 (0.290–0.610) (Table 2).

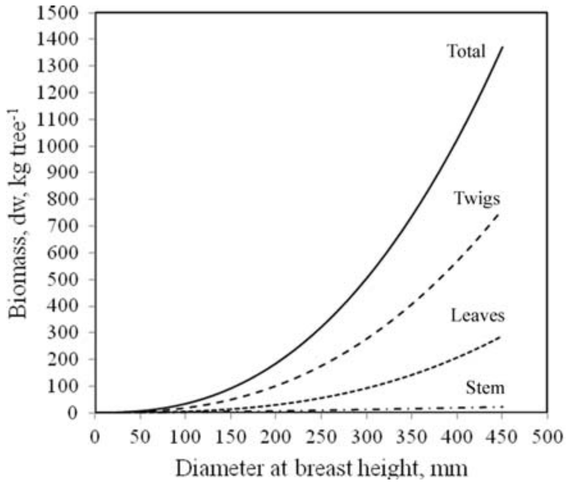

Fig. 2 Dry mass production per tree, kg tree^{-1}, in relation to diameter at breast height (DBH), mm) of total, stem, twigs and leaves for sample trees of hybrid aspen stands growing on abandoned farmland

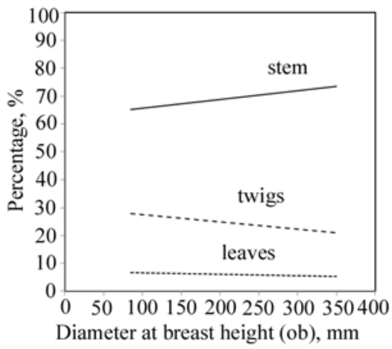

Fig. 3. Percentage of total tree dry weight accounted for by stem, twigs and leaves in relation to diameter at breast height (DBH; mm) for sample trees of hybrid aspens growing on farmland.

Table 4. Fresh-weight and dry-mass production (kg·tree^{-1}) and mean percentage of total tree fresh-weight and dry-weight accounted for by stem, twigs and leaves from sampled hybrid aspen trees

	Fresh-weight, kg·tree^{-1}				Percentage of total fresh-weight		
	Total	Stem	Twigs	Leaves	Stem	Twigs	Leaves
Mean±SD	411±225	286±163	101±69	24±13	70±10	24±9	6±1
Range	145-1185	89-859	23-255	11-71	50-85	7-46	4-9
	Dry-weight, kg tree^{-1}				Percentage of total dry-weight		
	Total	Stem	Twigs	Leaves	Stem	Twigs	Leaves
Mean±SD	218±120	157±90	53±36	9±5	72±10	24±10	4±1
Range	68-625	41-467	13-132	3-26	51-85	11-46	3-7

Biomass structure for hybrid aspen stands

Actual dry mass production per hectare for the stands was calculated (Table 5). The mean total dry mass above stump level was 135±53 t·ha^{-1} (42–219), and the mean MAI was 7±3 t·ha^{-1}·a^{-1} (3–13). The correlation (R^2=0.16, p<0.0001) between total dry mass production above stump level and DBH for hybrid aspen stands is illustrated in Fig. 4. Mean leaf area index (LAI) was 2.24±0.58 (0.68–3.35) (Table 6).

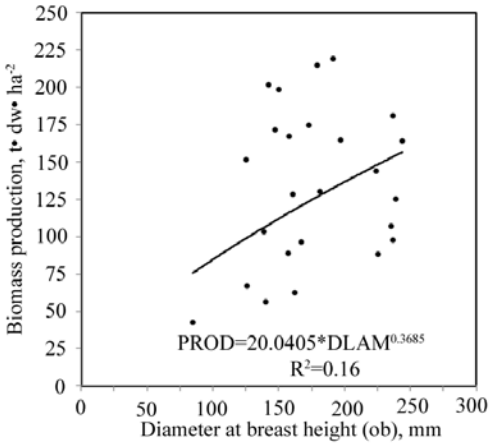

Fig. 4 Total dry mass production (PROD) above stump level in relation to diameter at breast height for hybrid aspen stands growing on abandoned farmland

Table 5. Dry-mass production (t·ha^{-1}) and mean annual increment (MAI; t·ha^{-1}·a^{-1}) of whole hybrid aspen stands.

Plot no.	Total	Stem	Twigs	Leaves	MAI
1	67.0	40.6	18.1	2.0	3.5
2	219.3	161.0	60.4	8.0	12.2
3	144.0	107.3	37.7	5.3	7.6
4	97.5	73.1	25.1	3.5	5.1
5	96.6	68.3	27.1	3.4	5.1
6	56.6	38.3	16.3	1.9	3.0
7	167.2	115.7	46.8	5.9	9.8
8	151.8	104.9	46.7	5.4	8.9
9	88.7	62.6	25.4	3.1	5.2
10	164.9	122.7	45.4	6.1	7.2
11	174.9	123.3	48.2	6.1	9.2
12	171.6	114.3	47.8	5.8	9.0
13	128.3	89.6	36.1	4.5	7.5
14	106.9	80.8	27.9	3.9	6.3
15	62.4	44.7	18.0	2.2	3.1
16	180.7	131.9	45.3	6.4	10.0
17	42.3	27.3	14.3	1.4	2.8
18	198.4	135.4	56.0	6.8	13.2
19	201.6	143.9	61.1	7.2	12.6
20	214.7	154.3	59.5	7.7	11.9
21	88.5	57.6	20.2	2.8	2.8
22	125.2	80.5	27.5	3.9	3.9
23	164.2	106.4	36.1	5.2	5.2
24	130.3	77.4	29.7	3.9	3.9
Mean±SD	135±53	94±37	37±14	5±2	7±3
Range	42-219	27-161	16-61	1-8	3-13
Percentage of total dry-weight					
Mean±SD		70±2	27±2	3±1	
Range		64-72	25-33	3-4	

Table 6. Leaf area index (LAI) in hybrid aspen stands, individual leaf dry-weight (mg) and total leaf weight per tree (g), number of leaves per tree, projected leaf area (PLA; cm^2) and specific leaf area (SLA; cm^2·g^{-1}) of sample trees.

	LAI	Weight d.w.		No. of	PLA	SLA
		leaf^{-1} (mg)	leaves tree^{-1} (g)	leaves tree^{-1}	cm^2	(cm^2·g^{-1} d.w.)
Mean±SD	2.24±0.58	373±245	8324±4806	28306±20463	48.86±13.76	165.75±81.11
Range	0.68-3.35	174-1312	3500-26400	8197-81589	29.74-71.44	33.17-350.93

Discussion

Measured values in the present study represent actual dry weight biomass. In the present study, twig and leaf weight as a percentage of total hybrid aspen dry weight decreased with increasing tree diameter (Fig. 3). The mean standing biomass of hybrid aspen of 135±53 t·ha^{-1} (42–219), is within the range of other published figures (Table 7). However, in some cases, the results are not comparable, since the data are not presented with diameter as the dependent variable. Another problem is that yield

In the present study, the mean annual increment (MAI) of total dry weight was 7±3 (3-13) t·ha^{-1}·a^{-1}. These values are similar to those reported in other studies for stands of the same age (Table 7). When comparing the standing dry weight production above stump level with corresponding estimates made in previous studies, it is important to keep in mind that some of the stands in the present study had low numbers of stems depending on damages. Thus, a more relevant comparison is the relationship between DBH and mean single-tree dry weight values based on either whole-tree or tree-component data. On this basis, the dry weight production values obtained for hybrid aspen stands in the present study (Table 4) are similar to, or higher than, those in other reports (Table 7).

Mostly the low number of aspens in the studied stands is depending on the lack of efficient fence against the strong pressure by wild habitat mostly moose and hare. Furthermore the ground vegetation indicated a poor or missing soil treatment before planting. Other factors could be high dryness close to initial plantation time. There are no indications that the biomass production in stands growing in southern Sweden (nos. 21-23) is higher than in other parts of Sweden.

However in Nordic countries there are some other fast-growing broad leaf species, which may be suitable for biomass production. In Table 7 published biomass production of alder (*Alnus glutinosa* (L.) Gaertner; *Alnus incana* (L.) Moench), European aspen (*Populus tremula* L.) and birch (*Betula pendula* Roth; *Betula pubescens* Ehrh.) and hybrid poplar are presented. MAI for those species differ between 1 and 15 t·ha^{-1}·a^{-1}. Values for 10–30 year-old European aspen, alder and birch stands were: 3–14, 2–10 and 1–8 t·ha^{-1}·a^{-1} respectively. The stands were naturally regenerated and mostly growing on forest land and not managed. The area of studied stands was small but the number of stems per hectare was high >3000. After harvest natural regeneration by sprouts and suckers might produce as high biomass as the presented figures. Mai for 10-30-year-old hybrid poplar plantation growing on former farmland was 3–15 t·ha^{-1}·a^{-1}, which is similar to those found for hybrid aspen in the present

figures are presented in volume (m^3) instead of biomass. As a rough measure the volume figures can be converted to biomass by multiplying by 0.350. The standing biomass per hectare for some stands is big when studying the number of stems (1400-1600) and mean diameter (170–190 mm). However, mean diameters of 160 to 220 mm and corresponding stem numbers 1400–1700 per hectare are noted for European aspen (Johansson 1999). There were no indications of self regeneration neither in the present nor the previous studies. But generally most of these stands require thinning in order to maintain high productivity rate until final harvest.

study.

Hybrid aspen stems accounted for 72±10 (50–85)% of the total aboveground dry biomass in the stands examined in the present study, while twigs accounted for 24±9% and leaves for 4±1%. Similarly, other studies have reported proportions of 73% for stems and 27% for twigs of 7-year old hybrid aspens growing on former farmland in Estonia (Tullus et al. 2009). Rytter and Stener (2003) reported proportions 76% for stems and 24% for twigs and leaves in a 14-year-old hybrid aspen stands.

The basic density indicates the amount of solid wood produced by the tree. This is an important factor when choosing a suitable species or clone for commercial forest management. As shown in the material examined here the mean basic density for stems was 0.356±0.050 (0.295–0.494) g·cm^{-3}. The range of the values means that it may be possible to choose clones or species with a high basic density. Similar values have been reported: 0.348 g·cm^{-3} for hybrid aspens grown in southern Sweden (Rytter and Stener 2003), 0.380 g·cm^{-3} in another study of 26-year-old hybrid aspens (Ilstedt and Gullberg 1993). Elfving 1986a) reported basic density of 0.348 g·cm^{-3} for 26-year-old hybrid aspens growing in southern Sweden and in another study 0.355 g·cm^{-3} (on average) for 10-year old trees with DBH 60–160 mm growing in southern Sweden (Stener 1998). In two American studies (Einspahr et al. 1968; Einspahr and Wyckoff 1975) basic densities of 0.403 (0.367–481) and 0.410 g·cm^{-3} respectively were reported from Lake States.

Generally, the annual production of foliage has been estimated either on the basis of standing biomass or from litter-fall. In the present study, estimates of standing foliage dry weight were based on mean data for the trees with the best conditions for foliage growth in the stand e.g. samples were made in July-August. However, the foliage dry weight can be affected by factors other than tree height and diameter (Madgwick 1971). To understand how the canopy contributes to total photosynthesis, knowledge is needed on how the distribution of foliage varies among dominant, co-dominant and suppressed trees, as the stand develops. In a study by Woods et al. (1991) about statistical error

analysis for biomass and leaf area index estimations for trembling aspen they reported a range of 1.3 to 4.0. According to the report LAI did not show clear relationship with biomass amount, stand density or average stem diameter. These patterns are expected for an early succession, shade-intolerant species. LAI remained relatively constant once a full canopy was established about 8 years after clear cutting of the studied stands (Woods et al. 1991).

Table7. Above-ground biomass production by hybrid aspen trees and stands and other fast-growing broad leaf species in Nordic countries. Data from published literature in chronological order of publication.

Stand age, years	Tree weight, kg (mm)	Stand production $t \cdot ha^{-1}$	MAI, $t \cdot ha^{-1} \cdot a^{-1}$	Remarks	References
5	6.3			Finland	Yu et al. 2001
14	61.7 (154)	98.7	7.1	Sweden	Rytter and Stener 2003
11		77.0	7.0	Sweden	Karačić et al. 2003
14		42–168.0	3.0–12.0	Sweden	Rytter and Stener 2005
23		207.0	7.0	Sweden	Johnsson 1953
16	(146)	120.0	7.5	Norway	Langhammer 1973
30		117.0	3.9	Central Sweden	Eriksson 1984
28		168.0	6.0	Denmark	Jacobsen 1976
10	26.9 (87)	120.0	12.0	Germany	Liesebach et al. 1999
26		119.6–208.0	4.6–8.0	Southern Sweden	Istedt and Gullberg 1993
7	(31)	8.0	1.1	Estonia	Tullus et al. 2009
8	5.0	24.3	3.0	Sweden	Telenius 1999
7-15		19.6–76.5	2.8–5.1	Sweden	Rytter 2002
5		26.5	5.4	Rotation no. 1 Germany	Hofmann-Schielle et al. 1999
5		53.5	10.7	Rotation no. 2 Germany	
24	(185)	100.5	4.2	Sweden	Persson 1973
42	(310)	198.1	4.5	Sweden	
26		156.8	5.6	Southern Sweden	Elfving 1986a
32		169.6	5.3	Northern Sweden	Elfving 1986b
15		70.5	4.7	US	Einspahr 1984
5		27.0	5.4	Eastern Bavaria, Germany	Makeshein et al. 1989
European aspen (*Populus tremula* L.)					
5-24		14–162	2.9–9.1	Sweden	Johansson 1999a
26-91		28–501	1.2–7.0	Sweden	Johansson 2002
12		170	14.2	Finland	Paavilainen 1981
Common alder (*Alnus glutinous* (L.) Gaertner)					
4-36		5-140	0.5–7.7	Sweden	Johansson 1999
21-91		73–257	1.5–6.1	Sweden	Johansson 1999
Grey alder (*Alnus incana* (L.) Moench)					
5-35		3–140	0.7–9.9	Sweden	Johansson 1999
21-66		82–218	2.1–5.5	Sweden	Johansson 1999
5		15.9	6.4	Estonia	Uri et al. 2002
19		85	4.5	Finland	Hytönen and Saarsalmi 2009
Downy birch (*Betula pubescens* Ehrh.)					
6-20		7–61	0.6–5.1	Sweden	Johansson 1999
19		112	5.9	Finland	Hytönen and Saarsalmi 2009
20		35	1.7	Finland	Mälkönen and Saarsalmi 1982
Silver birch (*Betula pendula* Roth)					
8-32		6–175	0.7–8.44	Sweden	Johansson 1999
6		14	2.3	Sweden	Telenius 1999
14		59	4.2	Finland	Ferm and Kaunisto 1983
19		108	5.7	Finland	Hytönen and Saarsalmi 2009
Hybrid poplar					
6		45	7.5	Sweden	Telenius 1999
4-73		19–438	3–15	Sweden	Johansson and Karačić 2011

The mean leaf area index (LAI) for hybrid aspen in the present study was 2.24±0.58 (0.68–3.35). There are few LAI values reported for hybrid aspen but Johansson (2002) reported 2.45±0.66 (1.80–3.19) for 26 to 91-year-old European aspens (*Populus tremula* L.). Tadaki (1966) reported that a normal range of LAI for aspen is 2.6 (2-5). Pollard (1972) reported LAI of 2.4,

2.9 and 1.9 respectively on 5-, 15- and 52-year-old stands of trembling aspen (*Populus tremuloides* Michx.) growing in the Ottawa Valley (lat. 46º00' N. and long. 77º26' W.). Peterson et al. (1970) reported a LAI of 1.8 for trembling aspen growing in Alberta. According to Korner (1991) SLA varies greatly among species and is influenced by environmental conditions. In addition, SLA is an important leaf characteristic, since it is positively related to net assimilation rate (Korner 1991). The SLA for hybrid aspen in the present study was 161.7±81.1 (33–351) $cm^2 \cdot g^{-1}$ d.w. Tullus et al. (2007) reported SLA-values of 102 $cm^2 \cdot g^{-1}$ in a study of 5-year-old hybrid aspen stands in Estonia. Yu (2001) reported 137$cm^2 \cdot g^{-1}$ for a 5-year-old hybrid aspen clone trial. PLA is used for light interception studies. According to Ridge et al. (1986), Dunlap and Stettler (1998) and Taylor et al. (2001) the leaf size is a good indicator of biomass productivity in fast growing trees. In the present study the mean projected leaf area (PLA) for hybrid aspen leaf area was 48.9±13.8 cm^2 range 30–71. In the study by Tullus et al. (2007) PLA was 19 cm^2 for 5-year-old hybrid aspens and in a study by Yu (2001) PLA was 18 cm^2.

In spite of these stands were not managed and damaged by wild habitat mean MAI was 7 (3–13) $t \cdot ha^{-1} \cdot a^{-1}$. MAI values of >10 t ha^{-1} $year^{-1}$ are possible for hybrid aspen plantations, and rotation periods of 10–20 years have been shown to be economic and practical (Benson and Einspahr 1967). Most hybrid aspen plantations growing on farmland are located near populated areas. Therefore, transport distances tend to be short for these harvested biomass fuels. The biomass used for bioenergy can be sold to district heating plants or to neighbors using biomass as a fuel. After harvesting the stand, a lot of suckers (50,000–100,000 suckers$\cdot ha^{-1}$) will emerge (Rytter 2006). The biomass production of 4-year-old 57000 suckers ha^{-1} was 39 $t \cdot ha^{-1}$ corresponding to MAI = 9.5 $t \cdot ha^{-1} \cdot a^{-1}$. Small trees, such as 5–10 year-old suckers, can be harvested using modern machines and then chipped. Alternatively, such trees can be felled using a chainsaw or whole-tree harvesters.

Conclusions

In the hybrid aspen stands examined in the present study biomass production was 135±53 $t \cdot ha^{-1}$ with a range of 42–219 $t \cdot ha^{-1}$. The average basal area was 24.6±10.0 $m^2 \cdot ha^{-1}$ (7.1–42.6). The stands were mostly not managed and in some stands there were low number of stems per hectare caused by damages of wild habitats and poor initial soil preparations before planting. These findings indicate the need of proper soil treatment before planting and an efficient fence, which must frequently be observed. Overall the results indicate that there is a high potential for using hybrid aspen stands in Sweden for viable biomass production.

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